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Stellar and substellar mass function of the young open cluster candidates Alessi 5 and β Monocerotis

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Abstract. Although the stellar and substellar populations have been studied in various young and old open clusters, additional studies in clusters in the age range from 5 to 100 Myr is crucial (e.g. to give more constrains on initial mass function variation with improved statistics). Among the open cluster candidates from recent studies, two clusters are best suited for photometric survey of very-low mass stars and brown dwarfs, considering their youth and relative proximity: Alessi 5 (τ~40 Myr, d~400 pc) and β Monocerotis (τ~9.1 Myr, d~400 pc). For both clusters, we performed an optical and near-infrared photometric survey, and a virtual observatory survey. Our survey is predicted to be sensitive from the massive B main sequence stars down to brown dwarfs of 30 M_{Jup}. Here, we present and discuss preliminary results, including the mass function obtained for Alessi 5, which is surprisingly very similar to the mass function of the Hyades (τ~600 Myr), although they are of very different ages.

1. Introduction

Several studies over the past ten years have presented surveys of open clusters in order to study the mass function (MF) of stellar and substellar populations, including the Orion Nebula Cluster, σ Orionis, IC 2391, the Pleiades and the Praesepe, to list just a few examples. These studies are important since stars and brown dwarfs (BD)s in open clusters possess modest age and metalicity spreads and share a common distance, in comparisons with large uncertainties for the field stellar and substellar objects (Bastian et al. 2010). In addition, determination of the MF in clusters with different properties (e.g. different density and ages) has led some investigators to draw conclusions about the relative efficiency of possible BD formation mechanisms (Briceño et al. 2002; Chabrier 2003; Kroupa & Bouvier 2003; Kumar & Schmeja 2007; Boudreault & Bailer-Jones 2009).

Many earlier studies of the substellar MF have focused on young open clusters with ages less than ~5 Myr, and in many cases much younger ($\lesssim$1 Myr). This is partly

because BDs are bright when they are young, thus easing detection of the least massive objects. However, youth present difficulties: intra-cluster extinction plagues the determination of the intrinsic luminosity function from the measured photometry, and at these ages the BD models have large(r) uncertainties (Baraffe et al. 2002). Studies in older clusters ($\gtrsim$100 Myr) present difficulties too: lacking a significant nuclear energy source, BDs cool and get faint as they age, so deeper surveys are required to detect them, and low-mass objects evaporate from clusters by dynamical evaporation (de La Fuente Marcos & de La Fuente Marcos 2000; Adams et al. 2002; Bouvier et al. 2008). Clusters in the range of age 5–100 Ma are perfect tools for MF studies on the BDs and very low-mass star populations since (1) these objects are bright, (2) have not lost trace of initial condition due to dynamical mass segregation or dynamical evaporation and (3) low extinction is expected towards these clusters. Despite these advantages, only a few open clusters are known in this age range.

Some works have been performed to search for previously unknown open clusters. Among the open cluster candidates from Alessi et al. (2003) and Kharchenko et al. (2005), two clusters are best suited for photometric survey of very low-mass star and BDs considering their youth and relative proximity : Alessi 5 ($\tau \sim$40 Myr, $d \sim$400 pc; Alessi et al. 2003) and β Monocerotis ($\tau \sim 9$ Ma, $d \sim 400$ pc; Kharchenko et al. 2005). (This cluster is presented as "ASCC 24" in Kharchenko et al. (2005).) So far, no accurate studies of these two clusters have been performed.

2. Observations

2.1. Optical photometry: WFI observations, data reduction, astrometry and photometric calibration

Our survey consists of one single Wide Field Imager (WFI) field of size 34×33 arcmin^2, observed in wide band R_c, and medium band 770/19, 815/20, 856/14 and 914/27 (where the filter name notation is central wavelength on the full width at half maximum, FWHM, in nm). This gives a total coverage of 0.26 deg^2 observed in all five bands, centred on the brightest stars of each cluster candidate. The data reduction and photometric calibration was performed in a similar way as presented in Boudreault & Bailer-Jones (2009). To correct for Earth-atmospheric absorption on the photometry, we observed the spectrophotometric standard stars observed were LTT 3864 and 4364.

For our β Mon and Alessi 5 observations, the 5σ detection limits of our survey are R_c=22.9 mag, which correspond to ~30 M_{Jup} according to our dust-free isochrone. The root mean square accuracy of our astrometric solution was 0.15–0.20.

2.2. Near infrared photometry: Ω2k and and 2MASS

The near infrared observations were performed only for β Mon. There were made using four Omega 2000 (Ω2k) pointing on the 3.5m telescope at Calar Alto, Spain, with observation runs of several nights in December 2008 and December 2009, covering the WFI pointing. The data reduction and photometric calibration of our near infrared photometry with Ω2k was performed in a similar way as presented in Boudreault et al. (2010). The 5σ detection limit at J=20.7 mag corresponds to an object of ~30 M_{Jup} in β Mon. For our survey on Alessi 5, we used the J and K_s photometry from 2MASS.

3. Candidate Selection Procedure

The procedure to compute the masses and effective temperature based on photometry is done in a similar way as presented by Boudreault & Bailer-Jones (2009) and Boudreault et al. (2010).

In order to perform the selection of candidates, we compute an isochrones for both Alessi 5 and β Mon. We used the spectral energy distribution to derive the mass and effective temperature, $T_{\rm eff}$, assuming that all our photometric candidates belong to the clusters studied. We used evolutionary tracks from Baraffe et al. (1998) and atmosphere models from Hauschildt et al. (1999) (assuming a dust-free atmosphere; the NextGen model) to compute an isochrone for Alessi 5 using an age of 40 Myr, distance of 400 pc, a solar metalicity and neglecting the reddening ($E(B-V) = 0$ mag), and for β Mon using an age of 9.1 Myr, distance of 210 pc, a solar metalicity and neglecting the reddening.

Candidates were first selected from the CMD involving the wide band $R_{\rm c}$ and 913/27 for Alessi 5, and the wide bands $R_{\rm c}$ and J. The candidates are only objects within a selection area defines to include (1) error on the distance, (2) error on the age, (3) error on the photometry and (4) objects brighter than the isochrones by 0.753 mag in order to include unresolved binaries. In Fig. 1 we present the CMDs where candidates were selected. The Fig. 1 also show cluster member of Kharchenko et al. (2005) with a membership probability higer than 10%, based on proper motion.

The second stage of candidate selection was achieved using colour-colour diagrams using the $R_{\rm c}$, 815/20 and $K_{\rm s}$ bands for Alessi 5, and using the $R_{\rm c}$, 815/20 and J bands for β Mon (Fig. 2). Since colours are used here, the selection area is defined by the error on the age on the isochrones and by the error on the photometry. For clarity, we present a contour plot of the colour–colour diagram for both clusters.

As indicated previously, our determination of $T_{\rm eff}$ is based on the spectral energy distribution of each object and is independent of the assumed distance. The membership status of an object can therefore be assessed by comparing its observed magnitude in a band with its magnitude predicted from its $T_{\rm eff}$ and β Mon and Alessi 5's isochrone (which assumes a distance and an age). This selection step is only a verification of the consistency between the physical parameters obtained of the photometric cluster candidates with the physical properties assumed for the cluster itself when computing the isochrones. To avoid removing unresolved binaries that are real members of the cluster, we keep all objects with a computed magnitude of up to 0.753 mag brighter than the observed magnitude.

4. Results and discussions

4.1. Alessi 5

We obtain a total of 234 cluster candidates based on our deep photometric survey. The J and $K_{\rm s}$ photometry of 2MASS is shallower in terms of mass in Alessi 5 compared to our optical photometry. To compute the MF of Alessi 5 to the lowest mass bin reached without optical data, we have computed a MF using only the optical photometry with WFI. We present this MF on Fig. 3 (lower left panel) as crosses. We computed a second MF from the list of candidates that passes all selections criteria with near infrared J and $K_{\rm s}$ photometry from 2MASS (presented on Fig. 3, lower left panel, as filled triangles). For each mass bin, we computed the number of object removed by adding the J and $K_{\rm s}$

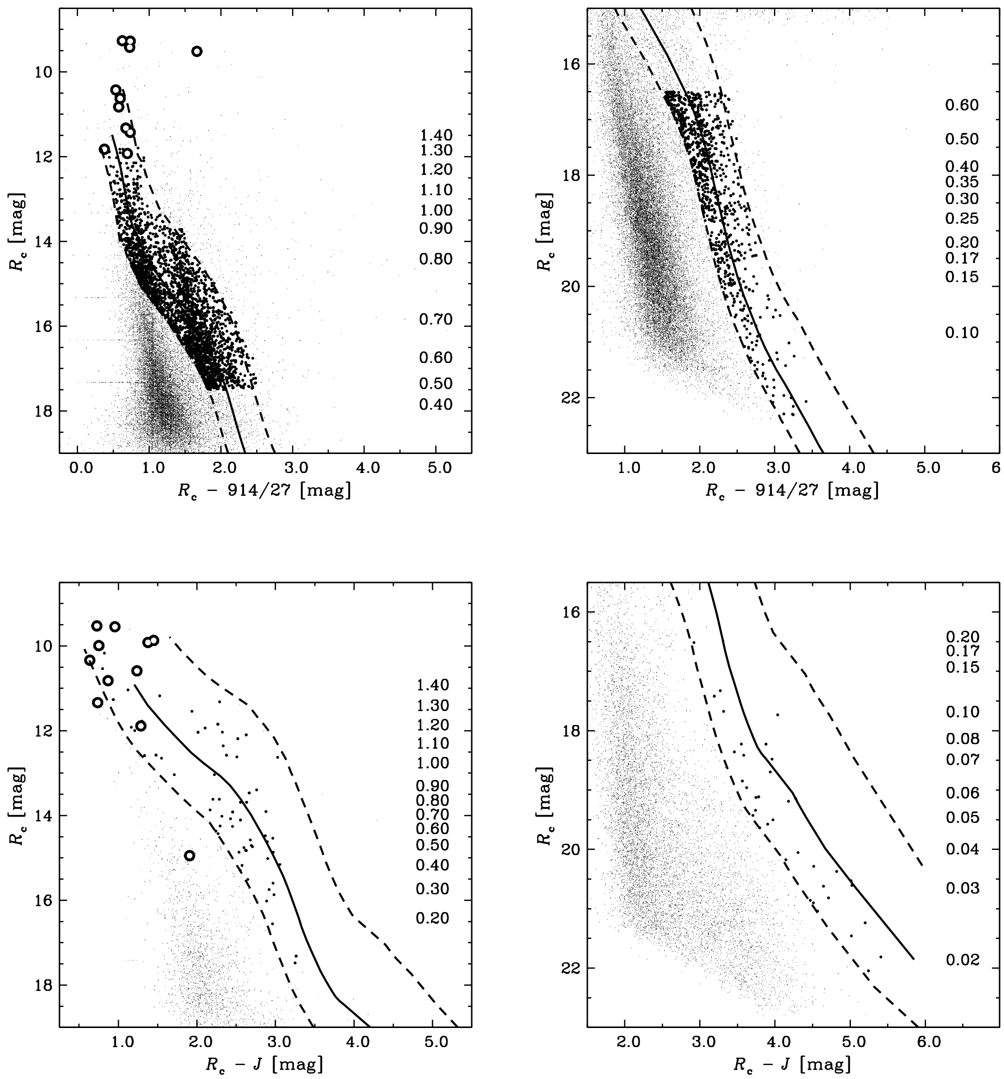

Figure 1. Colour–magnitude diagram for Alessi 5 (*top two panels*) with the R_c and 913/27 bands used in the selection procedure, and for β Mon (*top two panels*) with the R_c and J bands. We present the colour–magnitude diagrams from our shallow images (*left panels*) and deep images (*right panels*) we have taken. As solid lines we show the isochrone computed from an evolutionary model with a dust-free atmosphere (NextGen model). The numbers indicate the masses (in $M_\odot$) on the model sequence for various R_c magnitudes. We also show candidate cluster members that we detected in our survey from Kharchenko et al. (2005) (*circles*). The dashed lines delimit our selection band.

photometry of 2MASS to our selection process and mass determination (this is plotted as a function of mass in Fig. 3, top left panel). We fitted a power-law function to estimate the number of object that would be removed *if* we would had additional J and K_s photometry added to our optical photometry. The corresponding extension of the MF is given as large triangles (Fig. 3, lower left panel).

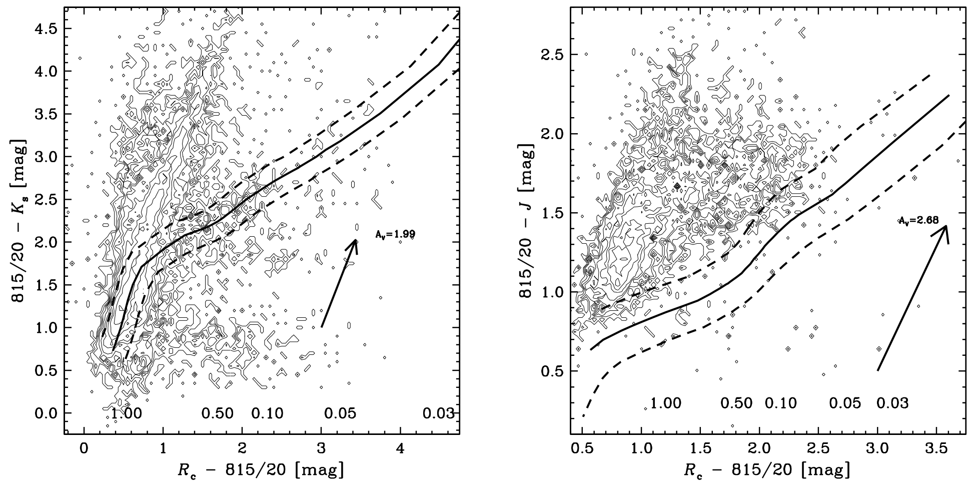

Figure 2. Colour–colour diagram for Alessi 5 (*left panel*) with the R_c, 815/20 and K_s bands used in the selection procedure, and for β Mon (*right panel*) with the R_c, 815/20 and J bands. As for Fig. 1, as solid lines we show the isochrone computed from an evolutionary model with a dust-free atmosphere and the dashed lines delimit our selection band. For Alessi 5, we clearly see a structure overlaping the isochrones for masses lover than ~0.6 $M_{\odot}$. On the other hand, we don't observe any structure in the colour–colour diagram of β Mon that overlap with the isochrone.

In Fig. 3 (right panel) we compare the MF of Alessi 5 with the MF of the open cluster NGC 2546 and the Hyades. The MF of Alessi 5 is surprisingly similar to the MF of the Hyades (Bouvier et al. 2008) with a decrease in the MF below ~0.6 $M_{\odot}$, although they are of very different ages (with about 40 and 600 Myr respectively). This support the conclusion that initial conditions are more likely to influence the shape of the MF more significantly than dynamical evolution. In addition, the MF of Alessi 5 shows some similarities with the MF of NGC 2547 (Jeffries et al. 2004): both show a decrease in the MF below ~0.6 $M_{\odot}$ and both open clusters present a peak at 0.7–1.0 $M_{\odot}$. It was shown by Boudreault & Bailer-Jones (2009) that this peak is due to red giant background contaminants.

4.2. β Mon

We obtain a total number of object of 19 candidates from our deep photometric survey in β Mon. Considering this and the absence of any structure in the colour-colour diagram of β Mon (see Fig. 2), we conclude that were is no cluster towards β Mon. This is further confirmed with our virtual observatory study in the following section.

5. Virtual Observatory study

We performed a 6.3 deg^2 Aladin-based virtual observatory analysis of the high-mass (about 8 to 1 $M_{\odot}$) population of stars in the Tycho-2 catalogue over both clusters. We use near infrared-optical CMDs (presented in Fig. 4, top two panels), proper-motions, spatial location diagrams of the cross-matched Tycho-2 and 2MASS sources in the 1 deg-radius circular areas centred on HD 93010 A for Alessi 5 and on β Mon ABC for

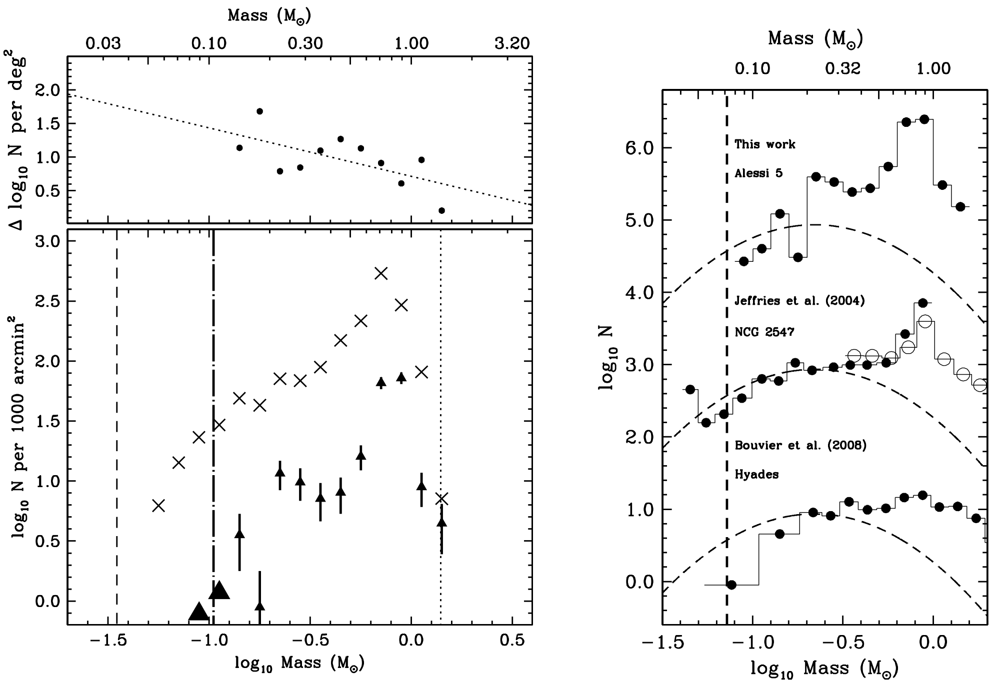

Figure 3. *Lower left panel.* MF of Alessi 5 using only our optical photometry (*crosses*) and combined with the near infrared photometry of 2MASS (*triangles*). The vertical dotted line represents the saturation limit of our optical survey, the vertical dashed line represent the 5 *sigma* detection limit of our optical survey, and the vertical dash-dotted line represents the 10 σ detection limit of 2MASS. Error bars are Poissonian arising from the number of objects observed in each bin. *Top left panel.* Difference of the number of object, in each mass bin, between the MF computed using our optical photometry and the MF computed using the combination of the optical data from WFI and the near infrared JK_s data from 2MASS. *Lower left panel.* MF of Alessi 5 and of the Hyades and NGC 2547. We also show the galactic field star MF fit from Chabrier (2003) as a thin dashed line and the substellar limit as a thick dashed line. We have normalized all the MFs to the log-normal fit of Chabrier (2003) at $\sim$0.3 $M_\odot$ (log M=-0.5).

β Mon (presented in Fig. 4, bottom two panels), and normalized cumulative distributions. At a quick glance to the spatial distribution diagrams in Fig. 4, the "clustering" of Alessi 5 is obvious, with ten cluster members in the innermost 20 arcmin-radius circular area and only five early-type stars possibly not associated to the cluster. However, β Mon has only four cluster member candidates in the same 20 arcmin-radius circular area and up to twelve early-type stars homogeneously distributed in the corona between 40 and 60 arcmin to β Mon ABC.

From our virtual observatory studies, including our above analysis of the spatial distribution of the cluster candidates, we conclude that there is no real clustering around β Mon (i.e. *[KPR2004] 24 does not exist*), but confirm the existence of Alessi 5 around the early-type giant binary HD 93010 AB.

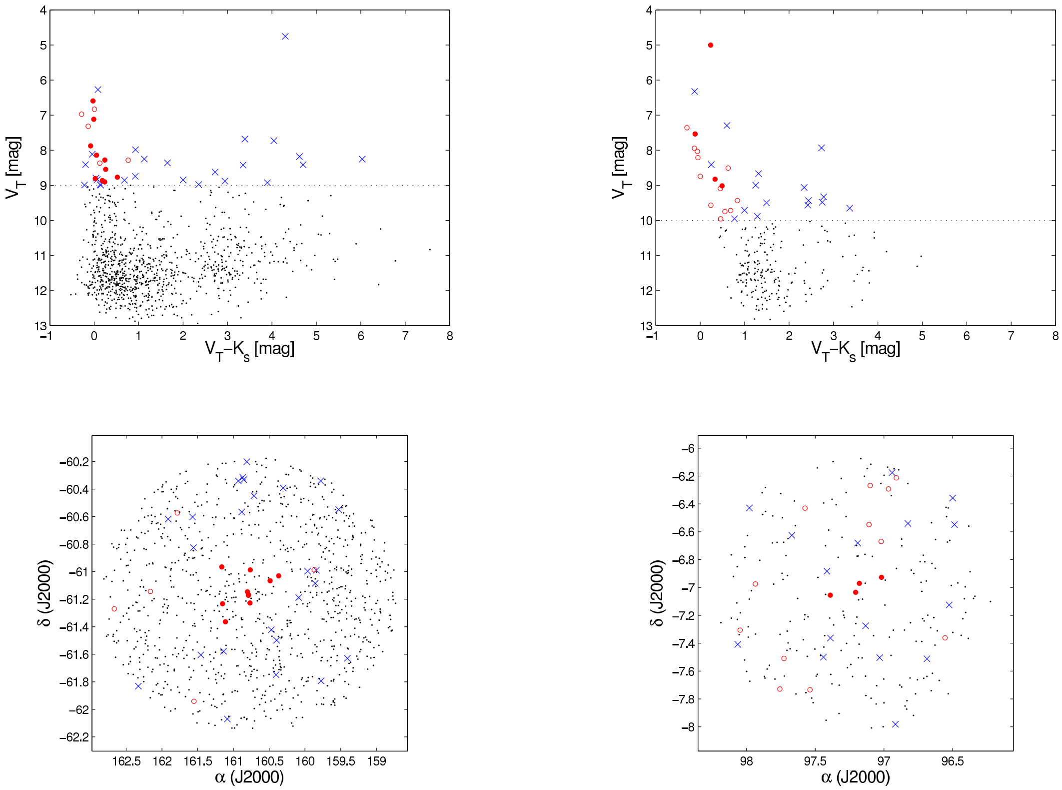

Figure 4. Near infrared-optical CMD of Alessi 5 (*top left panel*) and of β Mon (*top right panel*) using $V_{\rm T}$ and $K_{\rm S}$ band from our virtual observatory study. Spatial location diagrams of the cross-matched Tycho-2 and 2MASS sources in the 1 deg-radius circular areas centred on HD 93010 A (in the centre of Alessi 5, *lower left panel*), and β Mon ABC (*lower right panel*). In all the panels, (red) filled circles are cluster member candidates, (red) open circles are other early-type stars in the region, (blue) crosses are non-members based on abnormal proper motions and/or colours, and (black) small dots are the remaining cross-matched sources. For the CMDs, the horizontal dotted lines indicate the size of the virtual observatory analysis.

6. Conclusions

In this proceeding we presented the results of a survey to identify high- to low-mass stars and brown dwarf members of the recently discovered open cluster candidates Alessi 5 and β Mon. Our survey consisted of an optical and near infrared photometric survey covering 0.26 deg^2 and a virtual observatory survey of 6.3 deg^2 for both Alessi 5 and β Mon. With a 5σ detection limits of $R_{\rm c}$=22.9 mag, our survey is predicted to be sensitive from the massive B main sequence stars down to brown dwarfs of 30 M$_{\rm Jup}$ in Alessi 5 and in β Mon.

From our optical observations of Alessi 5 we identify 234 low-mass cluster member candidates from our WFI+2MASS survey and 10 high-mass candidates from our Aladin-based survey. From the list of candidates, we computed the MF of this cluster. The MF of Alessi 5 is surprisingly similar to the one of the Hyades, although they are of very different ages (with about 40 and 600 Myr respectively). This support the con-

clusion that initial conditions are more likely to influence the shape of the MF more significantly than dynamical evolution. In addition, the MF of Alessi 5 shows some similarities with the one of of NGC 2547.

As for the open cluster β Mon, we report a non detection of any clustering at the distance surveyed.

The results reported here will be presented with further details in an future publication (Boudreault & Caballero 2010, in prep).

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